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Liquid air fueled open–closed cycle Stirling engine

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ABSTRACT

An unconventional Stirling engine is proposed and its theoretical analysis is performed. The engine belongs to a "cryogenic heat engine" that is fueled by cryogenic medium. Conventional "cryogenic heat engine" employs liquid air as pressure source, but disregards its heat-absorbing ability. Therefore, its efficiency can only be improved by increasing vapor pressure, accordingly increasing the demand on pressure resistance and sealing. In the proposed engine, the added Stirling mechanism helps achieve its high efficiency and simplicity by utilizing the heat-absorbing ability of liquid air. On one hand, based on Stirling mechanism, gas in the hot space absorbs heat from atmosphere when expanding; gas in the cold space is cooled down by liquid air when compressed. Taking atmosphere as heat source and liquid air as heat sink, a closed Stirling cycle is formed. On the other hand, an exhaust port is set in the hot space. When expanding in the hot space, the vaporized gas is discharged through the exhaust port. Thus, an open cycle is established.

To model and analyze the system, the Schmidt theory is modified to describe temperature variation in the cold space, and irreversible characteristic of regenerator is incorporated in the thermodynamic model. The results obtained from the model show that under the same working pressure, the efficiency of the proposed engine is potentially higher than that of conventional ones and to achieve the same efficiency, the working pressure could be lower with the new mechanism. Its efficiency could be improved by reducing temperature difference between the regenerator and the cold/hot space, increasing the swept volume ratio, decreasing the liquid–gas ratio. To keep outputting work, the leading angle should be set in the region $[0, \pi]$.

1. Introduction

Recently zero emission vehicles have been explored extensively. They are generally categorized [1] into battery electric vehicles, hydrogen vehicles and air vehicles. The battery electric vehicles provide the highest efficiency, however the heavy metals pollution, high initial cost, long charging time have proved the limitation of them [2]. The superiority of hydrogen is high energy density, nevertheless, distribution and storage difficulties currently prevent its wide application [3]. Air vehicles can achieve an energy density close to that of the battery ones, furthermore, provides lower operation cost [4,5] and much less recharging time [6].

For the pressure air powered vehicles, the high energy density is achieved by increasing its storage pressure to several hundred atm. However, the pressure air powered engine is operated at several atm [7]. Generally, the pressure should be reduced from several hundred to several atm. The process results in over 50% energy loss and ice blocking of exhaust port [8]. Liquefaction of air is an alternation to achieve high energy density without the necessity of high storage pressure, avoiding the energy loss caused by pressure reduction, and this study is concerned with engines fueled by liquid air [9,10].

The energy stored in liquid air could be divided into cryogenic energy and expansion energy. At atmospheric pressure, the temperature of liquid air is below −196° (liquid nitrogen −196°, liquid oxygen −183°). It could be employed as heat sink to cooperate with atmosphere (heat source) to convert heat into work. Due to the existence of the temperature difference, the energy converted into work is referred as cryogenic energy. Knowlen [4] used liquid nitrogen as a heat sink for several cascaded topping closed Rankine cycles. Ordonez [6] employed closed Brayton cycle to convert the cryogenic energy to mechanic work. On the other hand, when liquid air is vaporized, the pressure of air would be increased, and the pressurized air could act as a pressure source to a piston or rotary motor. This part of energy is referred as expansion energy. Knowlen [5] utilizes liquid nitrogen as the working fluid for an open Rankine cycle to convert expansion energy to shaft work. Chen et al. [11] use the open cycle to analyze characteristics of this process.

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Nomenclature

p	pressure (Pa)
V	volume (m^3)
n	mass (kg)
θ	temperature (K)
Φ	phase angle
t	time (s)
W	work (kJ/kg)
Q	heat (kJ/kg)
E	energy (kJ/kg)
η	efficiency
H	enthalpy (kJ/kg)
ΔH	enthalpy heat of vaporization (kJ/kg)
C	molar heat capacity (kJ/kg K^{-1})
C_p	heat capacity at constant pressure (kJ/kg K^{-1})
C_v	heat capacity at constant volume (kJ/kg K^{-1})
T	period (s)
V_C	swept volume of displacer (m^3)
V_H	swept volume of power piston (m^3)
κ	swept volume ratio, VH/VC
α	leading angle
nC	defined in Table 1
$\Delta\theta_c$	temperature difference between the gas and the cold space (K)
$\Delta\theta_h$	temperature difference between the gas and the hot space (K)

Subscripts

a	atmosphere
c	cold space/cryogenic
h	hot space
g	gas state
l	liquid state
ph	phase change
0	Initial condition
r	regenerator
ep	expansion

Superscript

$*$	dimensionless variable

A limitation of liquid air fueled car is driving range, due to poor efficiency of the engine. For example, the engine [10,12,13] developed by the University of North Texas could only power a car for 24 km with up to 180 l of liquid nitrogen at operation pressure of 1.2 MPa. The engine produced 19 kJ of work per kilogram of nitrogen through a simple open cycle that converts expansion energy to shaft work. Theoretically, the energy of nitrogen is 760 kJ/kg [13]. The low energy efficiency (2.5%) is probably resulted from the very insufficient use of the cryogenic energy.

An open–closed cycle Stirling engine is proposed to employ a closed cycle to exploit the cryogenic energy and an open cycle to make use of the expansion energy.

For the closed cycle, Stirling engine is suitable to utilize. Generally, in practical use of Stirling engines, complex and expensive heaters made of stainless steel or ceramic to support high temperature prevents the wide application of Stirling engines [14]. Fortunately, the liquid air engine is operated in low temperature, thus Stirling engine could be feasible for the liquid air application.

For the open cycle, modifications should be made on conventional Stirling engines. A liquid air reservoir is integrated with the cold space of Stirling engine. The working gas flows into the reservoir and exchanges heat with liquid air directly. An exhaust port is set on the hot space. The vaporized air flows through the cold space to the hot space where it expands, and then flows out through the exhaust port.

The challenge of this work lies in the low temperature difference (LTD). For conventional Stirling engines, the temperature of their heat sources is not lower than 700° [15] and the atmosphere (20°) is taken as their heat sinks, thus the temperature difference is not smaller than 680°. However, the maximum temperature difference of the liquid air engine is 216°. If a Stirling engine runs in such a low temperature difference (LTD) [16,17], it is characterized as: the heat transfer surface of the displacer cylinder should be enlarged to absorb or to release more heat than that of normal Stirling engine by Rizzo [18] due to its low thermal efficiency (theoretically 40%, normal Stirling engine 70%). The low temperature difference condition would result in increasing weight and size of Stirling engines and stricter demand on heat transfer rate (1.75 times).

Table 1
Reference and dimensionless quantities.

Pressure	Volume	Temperature	Mass	Time	Energy
p_a	V_C	θ_a	$n_C = p_a \cdot V_C/(R\theta_a)$	T	$n_C R\theta_a$
$p^* = p/p_a$	$V^* = V/V_C$	$\theta^* = \theta/\theta_a$	$n^* = n/n_C$	$t^* = t/T$	$E^* = E/(n_C R\theta_a)$

The proposed Stirling engine will not face the situation of increasing size or mass. First, it operates below atmospheric temperature. And although its temperature difference is much lower than that of normal Stirling engines, its theoretical thermal efficiency (74%) is not lower. The demand on heat transfer rate is similar to normal ones.

Second, a new heat transfer structure helps enhance heat transfer. A conventional Stirling engine takes external heat source as power source, and wall-structure and tubular-structure are used to exchange heat. Tubular-structure is always adopted to increase heat exchange surface, bringing the problem of increasing dead volume. The proposed Stirling engine integrates liquid air reservoir with cold space, realizing direct heat-exchange of working gas and liquid air without thermal resistance. And heat transfer materials (such as porous copper) are integrated with displacer in cold space to enlarge the heat exchange surface without increasing dead volume. Moreover, with the movement of displacer, convection between working gas and liquid air in cold space is enhanced, benefiting their heat transfer.

The study aims to perform thermodynamic analysis of the open–closed cycle Stirling engine.

2. Energy of liquid air

Energy of liquid air discussed below is the energy that could be converted to mechanical work during the state change process of liquid air. The process could be divided into two stages in Fig. 1. In the first stage, the temperature of liquid air θ_c rises to that of atmosphere θ_a after absorbing enough heat from a Carnot engine. Through the absorbing process, the cryogenic energy is converted to mechanical work by the Carnot engine, and the liquid air is vaporized. In the second stage, the pressure of the air drops to that of atmosphere after expanding and the expansion energy is converted to mechanical work by an expander.

During the first stage, the state of the liquid air changes through three periods. In the first period, its temperature increases right